

A new method for extracting the bottom quark Yukawa coupling at the CERN Large Hadron Collider

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We propose a new method for measuring the $H \rightarrow b\bar{b}$ rate at the CERN Large Hadron Collider in a manner which would allow extraction of the b quark Yukawa coupling. Higgs boson production in purely electroweak $WHjj$ events is calculated. The Standard Model signal rate including decays $W \rightarrow \ell\nu$ and $H \rightarrow b\bar{b}$ is 11 fb for $M_H = 120$ GeV. It is possible to suppress the principal backgrounds, $Wb\bar{b}jj$ and $t\bar{t}jj$, to approximately the level of the signal. As the top quark Yukawa coupling does not appear in this process, it promises a reliable extraction of g_{Hbb} in the context of the Standard Model or some extensions, such as the MSSM.

The observation of electroweak symmetry breaking (ESB) in nature with the discovery of massive weak bosons is both a triumph and a tribulation of the Standard Model (SM) of particle interactions. While the SM has been incredibly successful in explaining the data from various experiments, it has also made very powerful predictions for other behavior that was later observed. To date there are no glaring contradictions with the SM, nor even any moderately uncomfortable ones. Despite this success, direct observation of the mechanism believed to be responsible for ESB, the Higgs boson, has not been made.

All quantum numbers of the SM Higgs boson are known from theory except for its mass, which is a free parameter. While fits to electroweak (EW) data suggest that the Higgs boson is considerably lighter than its theoretical upper limit of 1 TeV, probably on the order of 100 GeV [1], the current direct search exclusion limit of $M_H \gtrsim 114$ GeV [2] has pushed the SM Higgs boson mass above the EW fits central value. One may interpret this as a statement that we are on the verge of discovering the Higgs boson in present or near-future experiments.

If a new Higgs-like resonance is discovered at either the CERN Large Electron Positron collider, Fermilab's Tevatron machine or the soon to be built CERN Large Hadron Collider (LHC), it will be up to the LHC to determine the quantum numbers of the resonance and state with conviction whether it is the SM Higgs boson, a Higgs boson of an extension to the SM, or something else entirely. Of primary importance are the spin and couplings, which must be $SU(2)$ gauge couplings to the weak bosons and Yukawa couplings to fermions, proportional to the mass of the fermion. At the LHC, it will be fairly straightfor-

ward to determine the spin [3] as well as to extract the gauge couplings and total width of a SM-like Higgs boson [4]. Measuring the Yukawa couplings is more difficult. Higgs boson decays to fermions are substantial only for $M_H \lesssim 150$ GeV (except for $H \rightarrow t\bar{t}$, which is significant for $M_H \gtrsim 350$ GeV); heavier Higgs bosons decay dominantly to W, Z . However, the LHC will be able to measure the τ Yukawa coupling quite easily for $M_H \lesssim 150$ GeV [4].¹

This is made possible by the cleanliness and ease of observability of Higgs boson production in weak boson fusion (WBF), $pp \rightarrow qqVV + X \rightarrow qqH + X$, where the final state quarks appear as large invariant mass, high-pT tagging jets at far forward and backward rapidities in the detector, providing a unique signature with which to suppress the background rates. This technique would allow observation of decays to the final states $\gamma\gamma$ and $\tau^+\tau^-$ for $100 < M_H \lesssim 150$ GeV, and W^+W^- for $M_H \gtrsim 120$ GeV [8], with signal to background (S/B) rate ratios typically much better than 1/1. This is the only technique in which the decay $H \rightarrow \tau^+\tau^-$ could be observed in the SM. As such, it is the only method with which to extract a Higgs-fermion-fermion coupling. The technique of Ref. [4], which we rely on here, involves combining information from several Higgs boson channels to measure both the width to W pairs, Γ_W , which contains the $SU(2)$ gauge coupling of the Higgs boson to the weak bosons; and the total Higgs boson width, Γ_{tot} . The ratio of the $H \rightarrow \tau^+\tau^-$ rate to the $H \rightarrow W^+W^-$ rate in WBF is then proportional to Γ_τ/Γ_W , which allows one to determine the τ Yukawa coupling.

Measurement of additional Higgs Yukawa couplings is highly desirable. For example, in the MSSM there are five physical Higgs bosons, two of which have the same quantum numbers as the SM Higgs bosons, but can vary in mass, subject to the constraint that the lighter of the two states must have a mass $M_h \lesssim$

¹Earlier studies proposed using $b\bar{b}h, h \rightarrow b\bar{b}$ events to measure g_{Hbb} at the LHC, but only for very large $\tan(\beta)$ in the context of the MSSM [5]. However, detector simulations make questionable the feasibility of an effective use of this channel in practice [3].

135 GeV. As such, this state will typically have substantial rate for decays to fermions. In the MSSM however, Yukawa couplings of up-type and down-type fermions can be altered relative to each other already at tree level. This characteristic of the MSSM affects also the rare decay modes (e.g. $H \rightarrow \gamma\gamma$). In addition, large radiative corrections to the Yukawa couplings can modify the tree level decay rates considerably [6], e.g. causing “misalignment” of the couplings to b quarks and τ leptons. Thus, direct observation of more than one decay mode can provide a constraint on the model. Observation of $H \rightarrow c\bar{c}$ or other light fermions is not likely to be possible at the LHC. $H \rightarrow b\bar{b}$ will be extremely difficult, but possible in $t\bar{t}H$ associated production for Higgs boson masses below ~ 120 GeV [3]. However, this process suffers from the complication that both an up-type and down-type Yukawa coupling are convoluted, thus leaving the model largely undetermined.

Measurement of the $H \rightarrow b\bar{b}$ rate in WBF, $qqVV \rightarrow qqH \rightarrow b\bar{b}jj$, would be extremely difficult if not impossible, despite the rate being almost an order of magnitude larger than for the decay to tau pairs, as it would suffer from enormous QCD backgrounds. There is also the issue of triggering on $b\bar{b}jj$ events: they do not typically contain a high- p_T lepton, so may not pass a $\sum E_T$ trigger with great efficiency, thus the events would simply not be recorded. (An alternative is to design a dual tagging jet trigger.) Thus, another measurement of $H \rightarrow b\bar{b}$ involving a measured production coupling would be highly desirable.

We seek a process that provides a high- p_T lepton in addition to the far forward/backward tagging jets and the Higgs boson. The ideal choice is $WHjj$ production. Four classes of Feynman diagrams contribute to $pp \rightarrow WHjj + X$: WBF H production with W bremsstrahlung off a quark leg; WBF H production with additional W emission off the t -channel weak boson pair; and WBF W production and W bremsstrahlung where the Higgs boson is radiated off the W . Note that the $WHjj$ events we consider are *not* QCD corrections to WH associated production, but are pure EW processes; QCD corrections to WH events will ultimately constitute an enhancement of the signal, but will typically not survive the tagging jet cuts or minijet veto and so are neglected here, a conservative approximation.

We calculate the cross section for $pp \rightarrow WHjj + X$ at the LHC, $\sqrt{s} = 14$ TeV, using full tree level matrix elements for all EW subprocesses, including finite width and off-shell effects for $W \rightarrow \ell\nu$ ($\ell = e, \mu$), and finite width effects for $H \rightarrow b\bar{b}$. The matrix elements were generated by MADGRAPH [9]. The Higgs boson NLO decay and total widths are corrected via input from HDECAY [10]. CTEQ4L structure functions [11] are employed with a choice of factorization scale $\mu_{f_i} = p_{T_i}$ of the outgoing tagging jets. To provide realistic resolu-

TABLE I. Cross sections (fb) for the $WHjj$ signal as a function of Higgs boson mass. Shown on successive lines are the inclusive rate without W or H decays, the Higgs boson branching ratio to $b\bar{b}$, and the inclusive rate multiplied by the $H \rightarrow b\bar{b}$ and $W \rightarrow e\nu, \mu\nu$ branching ratios.

M_H	110	120	130	140	150
inclusive	84	80	76	72	70
$B_H(b\bar{b})$	0.77	0.67	0.52	0.33	0.17
$B_W \cdot B_H \cdot \sigma$	13.9	11.2	8.6	5.1	2.5

tion of the $b\bar{b}$ invariant mass, gaussian smearing of final state particle four-momenta is employed according to ATLAS expectations [3]. We do not decay the bottom quarks explicitly, but do include a parameterized energy loss distribution to make a more realistic simulation of observed final state momenta, overall missing momentum and $b\bar{b}$ invariant mass. As some Feynman diagrams with a t -channel photon contribute, the total cross section, shown as a function of M_H in line 1 of Table I, is calculated with an explicit initial-final state quark pair $Q_{ij}^2 > 100$ GeV² to avoid the singularity from the photon propagator. This cut introduces a small uncertainty for the total rate without cuts, $\approx \pm 15\%$ for varying the Q^2 cut by a factor of 2 (1/2). It does not, however, affect the cross sections with cuts.

The total signal rate appears to be large enough to obtain a significant data sample. However, to determine whether this measurement is realistic, we calculate the cross section for the main background which can mimic the signal. The largest resonant backgrounds are QCD and EW $WZjj$; $Z \rightarrow b\bar{b}$ production, but in these cases the Z pole is well-separated from the Higgs boson resonance so the overlap should be minimal given the superior detector jet resolutions. Thus, we ignore these backgrounds for the present viability check and instead concentrate on the largest backgrounds to this signal: nonresonant QCD $Wb\bar{b}jj$ production, and $t\bar{t} + jets$ events, where both W 's from the top quarks decay leptonically (e or μ) and one of the leptons is too low in p_T to be observed; we take this cut to be $p_T(l, min) < 10$ GeV for the simple check here. The latter events consist of QCD corrections to $t\bar{t}$ production, but are completely perturbative in the phase space region of interest, as the QCD radiation can appear in the detector as far forward/backward tagging jets. In addition, there are tree level processes that do not correspond to initial or final state gluon radiation. Other potential backgrounds are primarily irreducible, or fake signatures, which are naturally expected to be subdominant to continuum production.

We calculate the $Wb\bar{b}jj$ and $t\bar{t}jj$ rates using exact tree-level matrix elements, constructed using MADGRAPH [9] for the former, and the latter from Ref. [12]. We include top quark and W leptonic decays to e, μ in

the matrix elements. CTEQ4L structure functions [11] are employed throughout. We take the factorization scale for the $Wb\bar{b}jj$ background the same as the signal, and the renormalization scale $\mu_r = \sqrt{\mu_{f,1} \cdot \mu_{f,2}}$. For the $t\bar{t}jj$ background, $\mu_f = \min(E_T)$ of the jets/top quarks, and renormalization scale $\mu_r = E_T(\text{jet/top})$, with one factor of α_s taken from each of the outgoing jets/top quarks. In all cases, $\alpha_s(M_Z) = 0.118$ with 1-loop running.

The basic WBF signature requires the two tagging jets to be at high rapidity and in opposite hemispheres of the detector, and the H, W decay products to be central and in between the tagging jets. The kinematic requirements for the “rapidity gap” level of cuts are as follows:

$$\begin{aligned} p_{T_j} &\geq 30 \text{ GeV}, \quad |\eta_j| \leq 5.0, \quad \Delta R_{jj} \geq 0.6, \\ p_{T_b} &\geq 15 \text{ GeV}, \quad |\eta_b| \leq 2.5, \quad \Delta R_{jb} \geq 0.6, \\ p_{T_\ell} &\geq 20 \text{ GeV}, \quad |\eta_\ell| \leq 2.5, \quad \Delta R_{j\ell, b\ell} \geq 0.6, \\ \eta_{j, \min} + 0.7 &< \eta_{b, \ell} < \eta_{j, \max} - 0.7, \\ \eta_{j_1} \cdot \eta_{j_2} &< 0, \quad \Delta \eta_{tags} = |\eta_{j_1} - \eta_{j_2}| \geq 4.4. \end{aligned} \quad (1)$$

The results for $M_H = 120$ GeV are shown in the first column of Table II. At this level the backgrounds are already somewhat manageable, but we observe that the QCD $Wb\bar{b}jj$ background is dominated by low invariant masses of the tagging jet pair and low- p_T b jets, so we impose a minimum tagging dijet mass and an additional staggered $p_T(b)$ cut to reduce this contribution:

$$m_{jj} > 600 \text{ GeV}, \quad p_T(b_1, b_2) > 50, 20 \text{ GeV}. \quad (2)$$

The m_{jj} cut is also somewhat effective against $t\bar{t}jj$ events, as shown in the second column of Table II. Furthermore, there are two strikingly different characteristics of the signal v. the $t\bar{t}jj$ background: the latter events have significantly higher \not{p}_T on average; and they do not exhibit a Jacobian peak in the $m_T(\ell, \not{p}_T)$ distribution, a characteristic of W decays. Both features are due to the fact that by suppressing observation of the second charged lepton, the neutrino from that W 's decay has significantly enhanced transverse momentum, which is unobserved, and greatly distorts the $m_T(\ell, \not{p}_T)$ distribution. We choose maximum cutoff values for both observables as follows:

$$\not{p}_T < 100 \text{ GeV}, \quad m_T(\ell, \not{p}_T) < 100 \text{ GeV}. \quad (3)$$

The result is shown in the third column of Table II.

A final cut that may be utilized is to reject any candidate event if it contains additional central QCD (jet) activity of moderate p_T : a minijet [13]. Studies of the minijet rate for WBF, EW and QCD events can be found in Refs. [14,8] and references therein. Here, we simply apply the results from those studies. The probability of a signal event surviving a minijet veto, $p_T^{\text{veto}}(j) > 20$ GeV, is estimated to be 75%,

slightly lower than that typical of WBF Higgs boson events, because the W bremsstrahlung components of $WHjj$ events can slightly enhance the minijet activity. The probability of a $t\bar{t}jj$ background event surviving a minijet veto is much lower, only about 30%; previous studies have indicated it may be even better than this for $t\bar{t} + \text{jets}$ events, but we choose to remain conservative for our proof of concept estimates here. This allows us to achieve a S/B rate of 1/2 for $M_H = 120$ GeV, considering only the two major backgrounds for this demonstration.

At this stage, shown in the fourth column of Table II, the situation appears quite good. However, in reality only about 25% of these events will be captured in the data sample due to detector efficiencies. We take the expected values for ATLAS and CMS to be 86% for each tagging jet, 95% for the charged lepton, and 60% for each b quark tag. We assume 100 fb^{-1} of data for each of two experiments, as in Ref. [4]. Our result at this point is comparable to that expected for the $t\bar{t}H; H \rightarrow b\bar{b}$ channel with $M_H = 120$ GeV: ATLAS expects the significance to be 3.6σ , with S/B $\sim 1/3$ [3]. However, the $b\bar{b}$ mass peak in $t\bar{t}H$ events does not clearly stand out, and again, the value g_{Hbb} is not easily extractable due to convolution with the top quark coupling.

To illustrate that our method would not be simply a counting experiment, rather a distinct resonance could be observed, Fig. 1 shows the invariant mass spectrum for the tagged b quark pair. The $Wb\bar{b}jj$ and $t\bar{t}jj$ background distributions combined are monotonically decreasing above $m_{b\bar{b}} = 80$ GeV, allowing the signal to present a clear peak in the spectrum for an intermediate mass Higgs boson.

We can make a preliminary rough estimate of the uncertainty in the measurement by calculating $\Delta\sigma/\sigma \approx \sqrt{N_S + N_B}/N_S \oplus 20\%$, including a 20% systematic uncertainty in the backgrounds. This yields about a 35% overall uncertainty in the cross section measurement for $M_H = 120$ GeV. As this error will dominate the extraction of $\Gamma(H \rightarrow b\bar{b})$, we may expect the overall measurement error for the partial width to b quarks to be $\mathcal{O}(50\%)$ for a Higgs boson of this mass. More precise estimates must wait for a more complete consideration of the signal and backgrounds [15].

We have demonstrated the feasibility of a measurement of the $H \rightarrow b\bar{b}$ decay rate at the LHC in a moderate background environment with reasonable luminosity, in a way that would allow extraction of the bottom quark Yukawa coupling. The technique shows promise for Higgs boson masses in the range of applicability to the MSSM, but would also be accessible in the SM or other SM-like extensions. More importantly, it does this independently of up-type Yukawa couplings (e.g. top quark), thus reducing model dependence. Due to the accuracy with which g_{HWW} ,

TABLE II. Cross sections (fb) for the $WHjj$ signal with $M_H = 120$ GeV, and QCD $Wb\bar{b}jj$ and $t\bar{t}jj$ principal backgrounds, at various levels of cuts. Also shown are the progression of S/B, statistical significance in Gaussian sigma, and an estimate of uncertainty in the measured cross section. 100 fb^{-1} of data for each of two experiments is assumed, as in Ref. [4]. A mass bin $100 < m_{b\bar{b}} < 130$ GeV is implicit for all levels of cuts, which captures about 80% of the signal. The systematic uncertainty is taken to be 20%.

cuts level	Eq. (1)	+ Eq. (2)	+ Eq. (3)	+ veto	$\times \epsilon_{\text{ID}} = 0.25$
$WHjj$ signal	1.4	1.4	1.1	0.81	0.20
$Wb\bar{b}jj$ bkg	8.8	5.7	4.3	1.30	0.32
$t\bar{t}jj$ bkg	4.9	3.7	1.2	0.35	0.09
S/B	1/10	1/7	1/5	1/2	1/2
σ_{Gauss}					4.4
$\Delta\sigma/\sigma$					35%

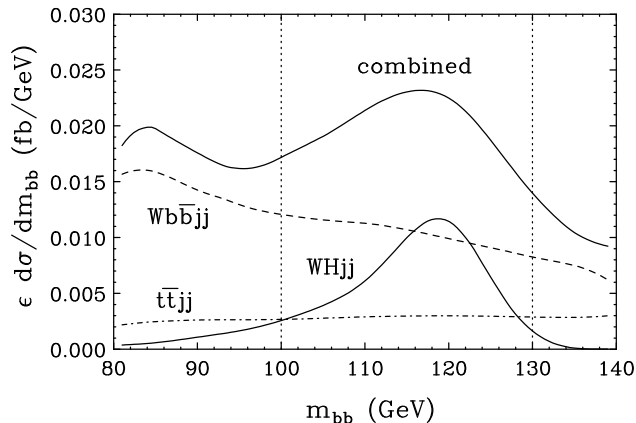


FIG. 1. $b\bar{b}$ invariant mass distribution of the $WHjj$ signal ($M_H = 120$ GeV), $Wb\bar{b}jj$ and $t\bar{t}jj$ backgrounds after all cuts, a minijet veto and efficiencies as discussed in the text. The combined signal and backgrounds are also shown. Vertical dotted lines denote the mass bin used for calculating statistical significance of the signal.

$g_{H\tau\tau}$ and the total Higgs boson width will be measured at the LHC [4], g_{Hbb} can be determined by taking either the ratio Γ_b/Γ_W or Γ_b/Γ_τ , depending on the Higgs boson mass and how SM-like the observed state is. To be sure, this channel will not provide a precision measurement, but all that is needed to constrain models other than the SM, or to rule out regions of the MSSM parameter space, is a nonzero width measurement. A more detailed study of this process including other backgrounds is underway [15]. Additional statistical significance may be added by using γHjj production, which is also being studied. Early indications are that the data sample would approximately double using both production modes.

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